

# **A CLIMATOLOGICAL STUDY OF COLD-AIR OUTBREAKS AND OTHER ATMOSPHERIC VARIABLES PERTINENT TO THE STUDY OF CLOUD STREET FORMATIONS OVER THE SOUTHEAST ATLANTIC COAST**

RUSSELL J. CHIBE, VALPARAISO UNIVERSITY (RUSS.CHIBE@VALPO.EDU)

Insofar as oceanic cloud streets (also referred to as maritime horizontal convective rolls) have been found to occur in conjunction with cold-air outbreaks over the southeast United States, and such cloud streets are to be studied by the COWEX project this winter, the following climatological study has been compiled so the expected behavior of cold-air outbreaks can be better understood. This study has been compiled under the supervision of Geary Schwemmer and David Miller in conjunction with the NASA/GSFC Summer Institute on Atmospheric and Hydrospheric Sciences 2000.

## **BACKGROUND**

The Convective Wave Experiment II (COWEX-II) is a study not yet undertaken by the Boundary Layer Lidar team at the NASA-Goddard Space Flight Center. The study seeks to determine, what, if any, role gravity waves play in the formation and/or maintenance of cloud streets. In order to better understand the dynamic structure of cloud streets, the team will fly above the cloud streets in an airplane equipped with the Large Aperture Scanning Airborne Lidar (LASAL), which will subsequently map out the three-dimensional aerosol structure of the lower troposphere and planetary boundary layer. Little is certain about the dynamic structure of cloud streets except that they commonly form off coastal areas during cold-air outbreaks as a result of convection and wind shear (Etling, 1993). This report seeks to further the understanding of cold-air outbreaks so that the COWEX team can make the most of its opportunities to obtain valuable data from cloud street phenomena.

## **DATA ASSIMILATION**

The data used for this study was provided by the NOAA-CIRES Climate Diagnostics Center. This dataset can be accessed via the World Wide Web at <http://www.cdc.noaa.gov/HistData/>. Specifically, surface air temperature anomalies over the United States (in color, shaded with overlying contours) were examined from the winter of 1980-1981 to 1999-2000. On the advice of Geary and Steve Palm, the dataset was limited to the

period between October 15<sup>th</sup> and March 15<sup>th</sup> for each season. The dataset was investigated skipping every other day until either outbreak conditions were observed (Figure 1) or an air mass likely to lead to outbreak conditions was observed approaching (Figure 2). Outbreak conditions are defined by a temperature anomaly of  $-5^{\circ}\text{C}$  or less observed off of the Carolina coast. Upon observing outbreak conditions, the following information was recorded: the initial date during which outbreak conditions were present, the length of the outbreak, the maximum anomaly observed for one day, the maximum cumulative anomaly observed when the daily anomalies are averaged, the state in which the maximum total anomaly was observed, and the coastal coverage of the outbreak, defined as the northernmost and southernmost coastal states which recorded an anomaly of  $-5^{\circ}\text{C}$ . This was done for a twenty-year period from October 15, 1980 to March 15, 2000, and the data were recorded in a notebook and subsequently entered into Microsoft Excel spreadsheets.

#### DATA ANALYSIS

After collecting the data into spreadsheets by year, the following analysis was performed. First, the coastal coverage was converted into a “coastal coverage variable” (CCV), which is defined as the approximate coastal distance between the two states divided by the total coastal distance. Second, “degree days” were calculated. Degree days are defined as the maximum average anomaly multiplied by the length of the outbreak. For example, if the total anomaly throughout the duration of a five-day outbreak is  $-17^{\circ}\text{C}$ , the outbreak generated 85 degree days. Such a variable helps to better incorporate both the severity and length of an outbreak into one value. Finally, outbreak days were calculated. This is the number of days during which outbreak conditions exist. Such a variable helps to differentiate between months with long outbreaks and months with short outbreaks.

With the above variables calculated, the data was organized into several datasets. First, all 283 outbreaks were compiled onto one “master list” spreadsheet, with the initial date, length, maximum one-day anomaly, maximum total anomaly, location of the maximum total anomaly (by state), CCV, and degree days recorded. Then the initial outbreak datasets, compiled by season, were reanalyzed. Several new statistics were tabulated for each month within the season (or, in the case of October and March, half-months). In a separate table, the number of outbreaks

beginning in each month was recorded. The number of outbreaks with a one-day anomaly of less than  $-20^{\circ}\text{C}$ , a total anomaly of less than  $-15^{\circ}\text{C}$ , long outbreaks of four days or more, and long outbreaks with a total anomaly of less than  $-15^{\circ}\text{C}$  were also tabulated. After that, the variables from the master list (except for outbreak degrees) were averaged. Outbreak degrees and outbreak days were each totaled. This gave a comprehensive breakdown of cold-air outbreak characteristics by month for each season (Figure 3).

After breaking down the outbreaks of each season by month, every outbreak over the nineteen-season period was re-organized by month, with each year's data for a given month organized in a table and then averaged to give a comprehensive picture of cold-air outbreak characteristics by month for the entire period (Figure 4). The monthly distribution of total outbreaks, outbreaks with a total anomaly greater than  $-15^{\circ}\text{C}$ , long outbreaks, total outbreak days, and total outbreak degrees, as well as average outbreak length and average total outbreak anomaly were each compiled in separate tables by month and season, so that one could observe both inter-annual variability by month as well as intra-annual variability within a given season (Figure 5). Seasonal totals were accumulated in a table to observe inter-annual variability by season (Figure 6). In order to compensate for the fact that October and March were only partially studied, and that December has three more days than February (three out of every four years), the odds of outbreak conditions existing on any day during a given month and the average anomaly for any day during which outbreak conditions exist (Figure 7) were calculated. To calculate the odds of outbreak, the average outbreak days for a given month were divided by the number of days observed for this study (being seventeen for October and fifteen for March). The average anomaly was calculated by dividing the average number of degree days for a given month by the average number of outbreak days for the same month.

## OBSERVATIONS

The difficulty in analyzing the various data collected on cold-air outbreaks is accounting for several inherent biases. When comparing different months, the different number of days for each must be taken into consideration. Another obstacle comes when averages themselves begin to be averaged. This proves to be a statistical problem, for if one outbreak occurs in October, and three in November, an average of accumulated data from October and November, respectively, does not represent the average of the four outbreaks. With this in mind, four main variables will be taken into consideration in making the following observations: odds of outbreak, average anomaly when outbreak conditions exist, average length of outbreak, and location of average maximum outbreak. These four variables provide a picture of cold-air outbreaks that is comprehensive without becoming cluttered.

The odds of outbreak variable, as described in the DATA ANALYSIS section of this paper, is rather simple. The variable represents the odds of outbreak conditions existing for any one day during the given month. This is the most accurate variable for calculating the likelihood of outbreak conditions because, unlike average number of outbreaks or average outbreak days, it takes into consideration the available days during which outbreaks could occur, rather than viewing each month as identical in length. With this in mind, both November and March are most likely subjected to outbreaks, with 30.33% of studied November and March days meeting the criteria for cold-air outbreaks. The next most likely month to incur such outbreaks is January (29.03%), and then December (25.81%). Now while these results may run contrary to common sense, which would suggest the coldest months (December and January) would have the most outbreaks, one must keep in mind that an outbreak is defined as a deviation from the average. As such, while a recorded temperature of 0°C (32°F) in Charlotte, NC, would be cold enough to register as a cold-air outbreak on January 10<sup>th</sup> (with a climatological average of 5°C), a recorded temperature of 5°C (41°F) is considered an outbreak of equal severity for March 10<sup>th</sup> (climatological average of 10°C). The attached graph offers a visual comparison of the odds of outbreak for each month (Figure 8).

While the odds of outbreak variable provides a means of understanding how often outbreaks occur, that is only part of the picture. Just as important to many researchers is the severity of the outbreak. This is best represented by calculating the average anomaly for days

during which outbreak conditions exist. In order to do this, the number of outbreak degrees recorded for a given month over the nineteen-year period was divided by the total number of outbreak days recorded for the same period. Since 1980, the month of December has experienced the most severe outbreaks, with an average maximum daily anomaly of  $-12.63^{\circ}\text{C}$ , or  $-22.7^{\circ}\text{F}$ , on days when outbreak conditions exist. In other words, if you find the geographical location with the largest negative temperature anomaly averaged over the duration of the outbreak, assign that value as the anomaly for each day of the outbreak, and do so for each subsequent outbreak, the average maximum daily anomaly would represent the average of each day's anomaly. After December, January's outbreaks were most severe, with an average maximum anomaly of  $12.49^{\circ}\text{C}$ , or  $22.5^{\circ}\text{F}$ . A full visual comparison is attached at the end of this report (Figure 9).

The odds of outbreak suggest that November and March are most prone to outbreaks, while the average anomaly on days during which outbreak conditions exist indicates that the most severe outbreaks occur in December and January. Neither of these addresses a significant aspect of cold air outbreaks: duration. Averaging the length of each recorded outbreak for the months studied revealed that March has the longest outbreaks, averaging 3.47 days per outbreak. December is second with an average length of 3.25 days. A graph of all six months is found at the end of this report (Figure 10). It should be noted that only twenty-five March outbreaks were studied, as opposed to thirty-nine December outbreaks. As such, the average lengths are somewhat unfairly skewed by one twenty-eight day outbreak which occurred in 1981. To adjust for this, two further graphs were generated. The first (Figure 11) removes the maximum value from each month's dataset, and averages the rest. In such a manner November is found to have the longest outbreaks, with an average of 2.97 days per outbreak. March falls to fourth with 2.68 days per outbreak, less than November, December (2.93 days per outbreak), and January (2.70). Since such a method is biased in favor of larger datasets, a second graph was generated in which the top and bottom 5% of each dataset were removed (Figure 12). The results of this method are virtually identical to the previous method. As such, we can conclude that November can expect the longest outbreaks, followed by December and January. However, it should be noted that outbreaks of longer than ten days have occurred in November, December, January, and March, and that outbreaks twenty days or longer have occurred in January and March, so extremes are possible.

At this point a rather clear picture of cold-air outbreaks has been formed. Still, one more aspect of cold-air outbreaks needs to be addressed. In this study, the severity of an outbreak is based on the maximum observed anomaly. Yet the maximum observed anomaly for one outbreak might be in Florida, while the maximum for another outbreak is in North Dakota. Two geographic variables have been considered in this study: the coastal coverage variable (CCV), and the state in which the maximum anomaly was observed. The CCV is useful for visualizing how great an area the outbreak covers. However, 54% of the observed outbreaks reached 100% coverage, and as such the CCV tells us little about specific locations of such outbreaks (Figure 13). It is therefore imperative that the specific locations of the maximum anomalies be examined. One must first remember that the geographic locations of maxima are still for periods during which outbreak conditions exist on the Carolina coast. The outbreak of February 2, 1987, while having a maximum negative anomaly in Texas, was still an outbreak over the Southeast Atlantic coast. The same is true of the October 18, 1992 outbreak, with a maximum in Michigan. With that in mind, the locations of the maxima are useful for two things. First, they give us an idea of how relevant the maximum is to our area of interest (a maximum anomaly of  $-20^{\circ}$  centered over Texas will not be as severe at the Wallops Flight Facility as an identical outbreak centered over North Carolina). Second, they give us an idea about the upper air structure of the outbreak. While difficult to quantify, observing the 500 millibar height fields for hundreds of outbreaks used in this study has revealed certain prominent characteristics shared by outbreaks with maxima in common regions.

The outbreaks were analyzed by region (Figures 14 and 15), both statistically and observationally. The outbreaks were also analyzed by the month of occurrence, according to the location of their maximum anomaly (Figure 16). Outbreaks with maxima over the central coast (North Carolina, Virginia) tend to be the result of digging troughs. While occasionally the trough will advect from the Central Plains, more often the case is that the trough digs from the eastern Great Lakes. In such a case temperature advection tends to come from the north as opposed to the east, causing an outbreak that appears with little warning, relative to other outbreaks. Such outbreaks are particularly prevalent in November, December, and January.

As the state of maximum anomaly moves further south along the coast (Georgia, Florida), the troughs tend to be deeper, making a sweeping motion from across the Plains prior to the outbreak. In such conditions, both the trough itself and the cold temperatures can be seen

advecting from the west. These outbreaks seem to offer more warning than their central counterparts. Such outbreaks are prominent in December, January, and February.

While not prominent in one specific month, the months of October through February all have observed between four and six outbreaks with maxima located in Texas in the past nineteen years. These outbreaks are characterized by a prominent ridge over the Rockies slowly advecting across the plains. Oftentimes, the flow east of the ridge, over the coast, is nearly zonal. Like outbreaks with maxima along the southern coast, these outbreaks can be easily observed advecting across the southeast United States.

Outbreaks in the northern Atlantic are very similar in structure to those over the central Atlantic coast. The main difference between the two is that, in the case of outbreaks centered over the northern Atlantic, the troughs dig and lift more quickly, and hence are of shorter duration. Such outbreaks occur occasionally in October, November and December, but are virtually non-existent from January on.

Identifying the type of outbreak based on the upper-air features is rather useful because outbreaks with anomaly maxima in the same region share certain characteristics. The longest outbreaks have anomaly maxima centered over the central Plains and the central Atlantic coast, and share the upper-air features of the North Carolina and Virginia outbreaks described above. The most severe outbreaks also happen to have maxima centered over the central Plains, with the southern Plains second and the central Atlantic region third highest in degree days.

#### FURTHER ANALYSIS

As described by LeMonte (1973), the presence of cold air is not the only requirement for cloud streets. Strong sea-air temperature differences and significant vertical wind shear are also major components of cloud street development. In order to complement the above outbreak climatology, buoy data off of the southeast Atlantic coast was closely examined. This data comes from the National Data Buoy Center and can be accessed by the public through the Internet at <http://www.ndbc.noaa.gov/climate.phtml>. Both sea-air temperature differences and peak wind gust records from four buoys off the Atlantic coast between Delaware and Florida were observed (Figure 17). While the buoys vary in their length of operation (buoy 44014 being the shortest with 26 months of data, and buoy 41004 being the longest with over fifteen years of

data), each helps to further round out our understanding of the variables that contribute to cloud streets.

The first variable examined was differences between sea surface and air temperatures (Figure 18). In all four cases, the difference between sea surface and air temperatures peaked in December, suggesting that the late fall and early winter months are more likely to generate cloud streets than the late winter months. The second variable examined was peak wind gusts (Figure 19). Cloud streets need both vertical shear and strong surface winds (LeMone, 1973), and peak wind gusts indicate, indirectly in the case of vertical shear and directly in the case of surface winds, the presence of both conditions. Peak wind gusts are also at a maximum in December for each buoy except the two southernmost (at which January and October, respectively, beat out December). Overall, this data also indicates the early part of winter as optimal for cloud street formation.

## CONCLUSION

While the exact conditions necessary for cloud streets are not fully known at this time, particularly severe cold-air outbreaks, combined with sufficient vertical wind shear in an unstable environment, are the most likely to produce such convective phenomena. With this in mind, the above observations suggest that several times and conditions are most suited for the observation and study of cloud streets. When looking at the odds of outbreak occurrence, November, December, and January would seem optimal. March is also likely to experience outbreaks, but by this time the ocean has cooled substantially, reducing the difference in sea surface and air temperatures, and consequently impeding convective processes. When looking at the average daily anomaly of cold-air outbreaks, December and January offer the most severe outbreaks. Geographical analysis of outbreak maxima suggest that, while the most severe outbreaks have maxima over the Plains, outbreaks with the strongest impact on the central and southern Atlantic coast should have maxima over that part of the Atlantic coast. These outbreaks are most likely to occur in November, December, and January. With these observations in mind, the greatest opportunity for cold-air outbreaks over the central and southern Atlantic coast, and subsequent cloud streets, appears to be between the months of November and January, when models show a 500-mb trough digging sharply down the coast from the eastern Great Lakes region.



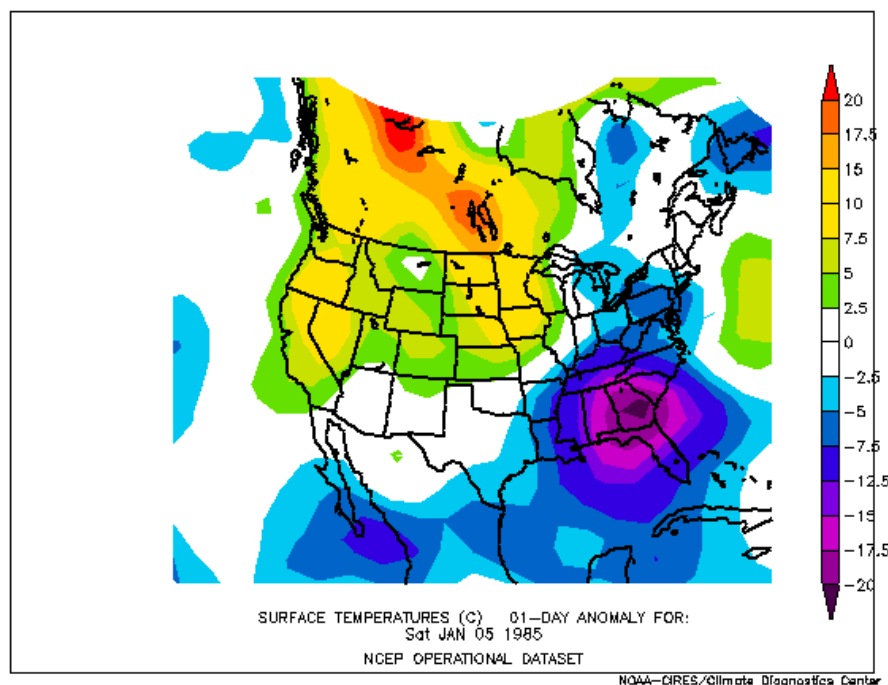
### PROPOSED FUTURE RESEARCH

While this study is a good starting point for understanding cold-air outbreaks as they pertain to cloud streets, other factors should be investigated to further our knowledge of such phenomena. While peak wind gusts give us an idea of convective processes, wind shear itself should also be examined, as it is a key component to cloud street formation. Also, cloud street occurrences, based on GOES visible imagery, should be examined, so that one can have a better grasp of what type of cold-air outbreaks are most likely to generate cloud streets.

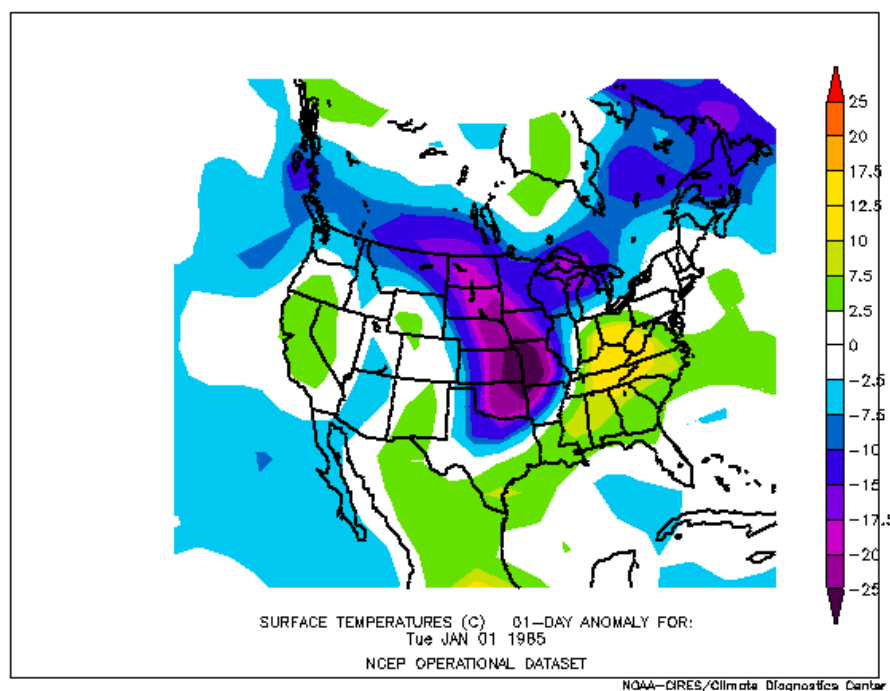
### WORKS CITED

Etling, D., and Brown, R.A., 1993: Roll vortices in the planetary boundary layer: a review. *Boundary-Layer Meteorology*, 65: 215-248.

LeMonte, Margaret Anne, 1973: The structure and dynamics of horizontal roll vortices in the planetary boundary layer. *Journal of the Atmospheric Sciences*, 30: 1077-1091.



**Figure 1. One-day image of cold air outbreak from NOAA-CIRES/Climate Diagnostics Center.**



**Figure 2. While outbreak conditions will likely exist in a day or two, the above image would not be considered an outbreak for this study.**

# COLD AIR OUTBREAKS, 15 OCT 1980-15 MARCH 1981

initial date	length of outbreak	max. one day anomaly	max. total anomaly	location of outbreak	CCV
10/24/80	4	-19	-14	NE	1.00
10/30/80	3	-20	-14	TX	0.76
11/11/80	3	-9	-8	DE	1.00
11/17/80	7	-37	-20	TX	1.00
11/26/80	5	-28	-13	TX	0.82
12/4/80	2	-17	-12	NH	1.00
12/11/80	2	-18	-13	ME	1.00
12/15/80	4	-16	-9	NC	1.00
12/20/80	5	-20	-14	ME	1.00
12/26/80	3	-17	-12	FL	1.00
12/30/80	21	-25	-15	NC	1.00
1/21/81	5	-11	-8	FL	1.00
1/29/81	10	-18	-12	NC	1.00
2/9/81	2	-10	-9	NC	0.90
2/12/81	4	-19	-14	TX	1.00
2/21/81	1	-10	-10	FL	0.39
2/24/81	4	-12	-10	FL	0.64
3/3/81	28	-16	-12	NC	1.00

## Breakdown by month:

month	number of outbreaks	number of outbreaks with 1-day anomaly $\leq -20^{\circ}\text{C}$	number of outbreaks with total anomaly $\leq -15^{\circ}\text{C}$	number of long outbreaks (four days or more)	number of long outbreaks with total anomaly $\leq -15^{\circ}\text{C}$	avg. length of outbreak (days)	avg. max. one day anomaly ( $^{\circ}\text{C}$ )	avg. max. total anomaly ( $^{\circ}\text{C}$ )	state of highest frequency of max. temp	avg. CCV	Degree days	Outbreak days
October	2	1	0	1	0	3.50	-19.50	-14.00	NE/TX	0.88	-84	6
November	3	2	1	2	1	5.00	-24.67	-13.67	TX	0.94	-243	16
December	6	2	1	3	1	6.17	-18.83	-12.50	ME/NC	1.00	-222	18
January	2	0	0	2	0	7.50	-14.50	-10.00	FL/NC	1.00	-361	27
February	4	0	0	2	0	2.75	-12.75	-10.75	FL	0.73	-208	18
March	1	0	0	1	0	28.00	-16.00	-12.00	NC	1.00	-156	13
TOTAL:	18	5	2	11	2	6.28	-17.89	-12.17	NC	0.92	-1274	98

**Figure 3. Example of outbreak records kept by season (in this case 1980-1981).**

# FEBRUARY COLD AIR OUTBREAKS, 1981-2000

season	number of outbreaks	number of outbreaks with 1-day anomaly $\leq -20^{\circ}\text{C}$	number of outbreaks with total anomaly $\leq -15^{\circ}\text{C}$	number of long outbreaks (four days or more)	number of long outbreaks with total anomaly $\leq -15^{\circ}\text{C}$	avg. length of outbreak (days)	avg. max. one day anomaly ( $^{\circ}\text{C}$ )	avg. max. total anomaly ( $^{\circ}\text{C}$ )	state of highest frequency of max. temp	avg. CCV	Degree days	Outbreak days
1980-81	4	0	0	2	0	2.75	-12.75	-10.75	FL	0.73	-208	18
1981-82	3	0	2	0	0	1.33	-15.33	-14.67	TX	0.59	-61	4
1982-83	3	1	1	2	0	4.00	-18.00	-12.33	FL/GA/TX	0.92	-140	12
1983-84	3	1	1	1	1	2.33	-12.67	-12.67	FL/MD/SC	0.72	-115	7
1984-85	2	2	1	0	0	3.00	-23.00	-14.00	FL	0.83	-84	6
1985-86	2	2	0	2	0	4.50	-24.00	-12.50	DE/TX	1.00	-127	10
1986-87	2	0	0	0	0	1.50	-6.50	-5.50	FL/NC	0.25	-14	3
1987-88	4	0	1	0	0	1.75	-13.25	-12.25	several	0.85	-86	7
1988-89	3	0	1	1	0	2.00	-15.67	-14.00	GA/ME/SC	0.93	-81	6
1989-90	1	0	0	0	0	2.00	-12.00	-9.00	VA	0.86	-18	2
1990-91	1	0	0	0	0	2.00	-17.00	-14.00	SC	0.93	-28	2
1991-92	1	0	0	0	0	2.00	-11.00	-5.00	NC	1.00	-10	2
1992-93	4	0	0	0	0	2.50	-13.75	-10.25	several	0.92	-98	9
1993-94	2	0	0	1	0	3.00	-13.00	-8.00	VA/WI	1.00	-50	6
1994-95	3	0	0	1	0	3.00	-12.33	-9.33	several	0.92	-88	9
1995-96	3	1	0	1	0	4.00	-16.67	-11.67	FL/ME/MS	1.00	-146	12
1996-97	1	0	0	0	0	2.00	-6.00	-6.00	NC	0.48	-12	2
1997-98	1	0	0	0	0	2.00	-9.00	-8.00	FL	0.39	-16	2
1998-99	2	0	0	1	0	4.00	-11.00	-8.50	NC	0.74	-74	8
1999-2000	2	0	0	0	0	1.50	-9.00	-9.00	FL/GA	0.39	-65	7
Average	2.35	0.35	0.35	0.60	0.05	2.62	-14.02	-10.94	FL	0.79	-76.05	6.70

**Figure 4. Example of outbreak records kept by month (in this case February).**

TOTAL OUTBREAK DAYS (Days during which cold air outbreak was present)						
	October	November	December	January	February	March
1980-81	6	16	18	27	18	13
1981-82	1	12	12	12	4	4
1982-83	2	9	5	7	12	5
1983-84	1	10	8	12	7	7
1984-85	0	14	4	19	6	3
1985-86	0	3	19	16	10	7
1986-87	0	2	0	4	3	5
1987-88	2	4	4	5	7	1
1988-89	1	1	9	2	6	3
1989-90	2	9	14	2	2	1
1990-91	3	3	0	1	2	1
1991-92	4	15	6	4	2	4
1992-93	5	10	7	0	9	6
1993-94	0	8	9	12	6	1
1994-95	4	3	1	7	9	3
1995-96	3	19	15	15	12	9
1996-97	2	20	6	10	2	0
1997-98	4	9	8	4	2	7
1998-99	3	8	8	8	8	10
1999-2000	5	7	7	13	7	1
Total	48	182	160	180	134	91
Average	2.4	9.1	8	9	6.7	4.55

**Figure 5. Record of total outbreak days by month for each season.**

#### ANNUAL COMPARISONS, WINTER 1980-81 - WINTER 1999-2000

season	ENSO	outbreaks	1-day anomaly < 20°C	total anomaly < -15°C	number of long outbreaks (four days or more)	long outbreaks with total anomaly < 15°C	avg. length of outbreak (days)	avg. max. one day anomaly (°C)	avg. max. total anomaly (°C)	state of highest frequency of max. temp	avg. CCV	Degree days	Outbreak days
1980-81		18	5	2	11	2	6.28	-17.89	-12.17	NC	0.92	-1274	98
1981-82		17	2	5	6	1	2.65	-13.94	-11.76	NC	0.77	-510	45
1982-83	W+	19	4	3	4	1	2.63	-15.74	-12.47	FL	0.77	-608	40
1983-84	C-	21	7	10	5	4	2.67	-19.00	-16.52	FL	0.85	-1052	45
1984-85	C-	14	5	4	5	2	3.29	-17.14	-11.57	FL	0.91	-559	46
1985-86		20	7	2	5	0	2.75	-16.40	-11.90	FL/GA	0.74	-680	55
1986-87	W	8	0	0	1	0	1.75	-10.00	-8.50	NC	0.52	-115	14
1987-88	WW-	13	0	1	0	0	1.92	-11.69	-10.00	NC	0.86	-222	23
1988-89	C+	10	1	2	1	0	2.10	-13.80	-11.30	SC	0.83	-238	22
1989-90		13	2	1	2	0	2.31	-13.85	-10.85	GA	0.78	-359	30
1990-91	W-	6	0	0	0	0	1.67	-10.50	-9.17	GANY	0.80	-90	10
1991-92	WW+	14	0	1	4	0	2.64	-11.79	-8.93	NC	0.82	-323	35
1992-93	W-	14	0	0	4	0	2.71	-11.29	-8.71	FL/NC	0.75	-335	37
1993-94	W-	14	1	1	4	1	2.57	-11.93	-8.93	NCVA	0.86	-327	36
1994-95	W	13	0	0	2	0	2.08	-10.08	-8.31	NC	0.69	-237	27
1995-96	C-	19	2	0	7	0	3.84	-13.16	-9.37	NC	0.86	-708	73
1996-97		11	1	1	6	1	3.64	-12.82	-9.91	NC	0.80	-408	40
1997-98	W+	11	1	1	3	1	3.09	-12.36	-9.55	FL	0.82	-339	34
1998-99	C/C+	13	0	0	6	0	3.54	-13.00	-9.77	NC	0.78	-452	45
1999-2000?		15	0	0	3	0	2.67	-11.60	-10.07	NC	0.73	-401	40
Average		14.15	1.90	1.70	3.95	0.65	2.84	-13.40	-10.49	NC	0.79	-461.85	39.75

**6. Comparison of outbreak variables by year (including ENSO analysis).**

**Figure**

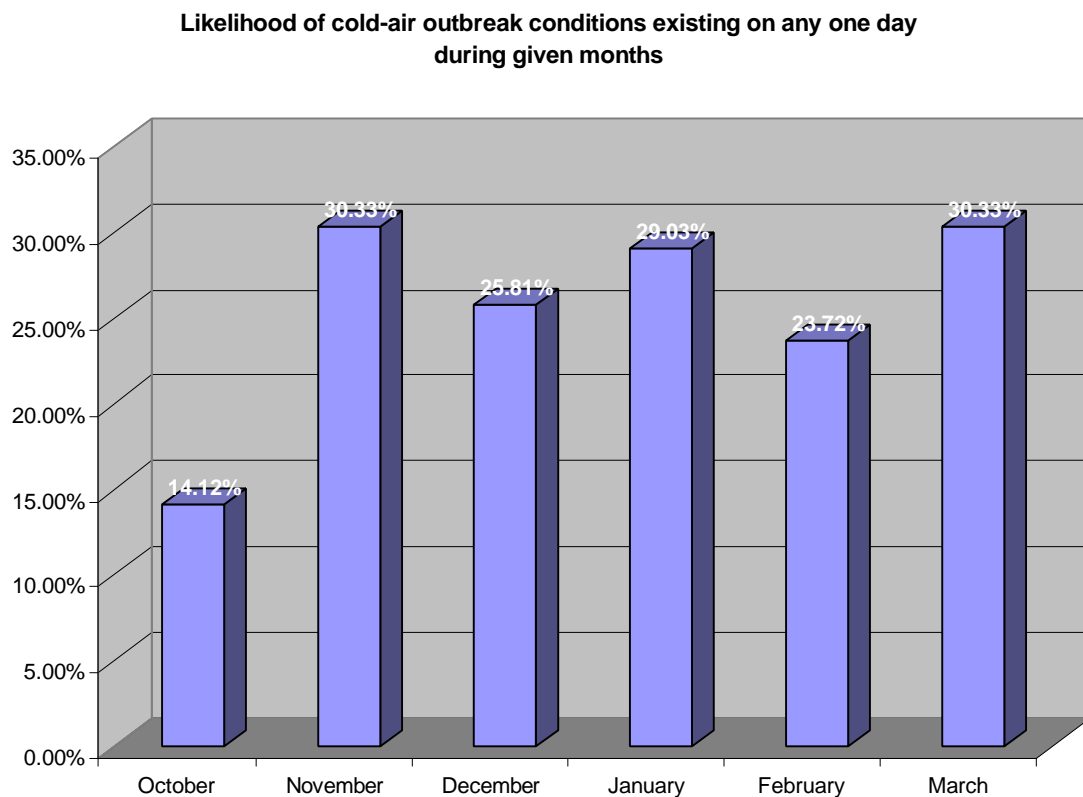
# ODDS OF OUTBREAK CONDITIONS EXISTING ON ANY DAY DURING A GIVEN MONTH

	October	November	December	January	February	March
avg. outbreak days	2.4	9.1	8	9	6.7	4.55
available days	17	30	31	31	28.25	15
odds	14.12%	30.33%	25.81%	29.03%	23.72%	30.33%

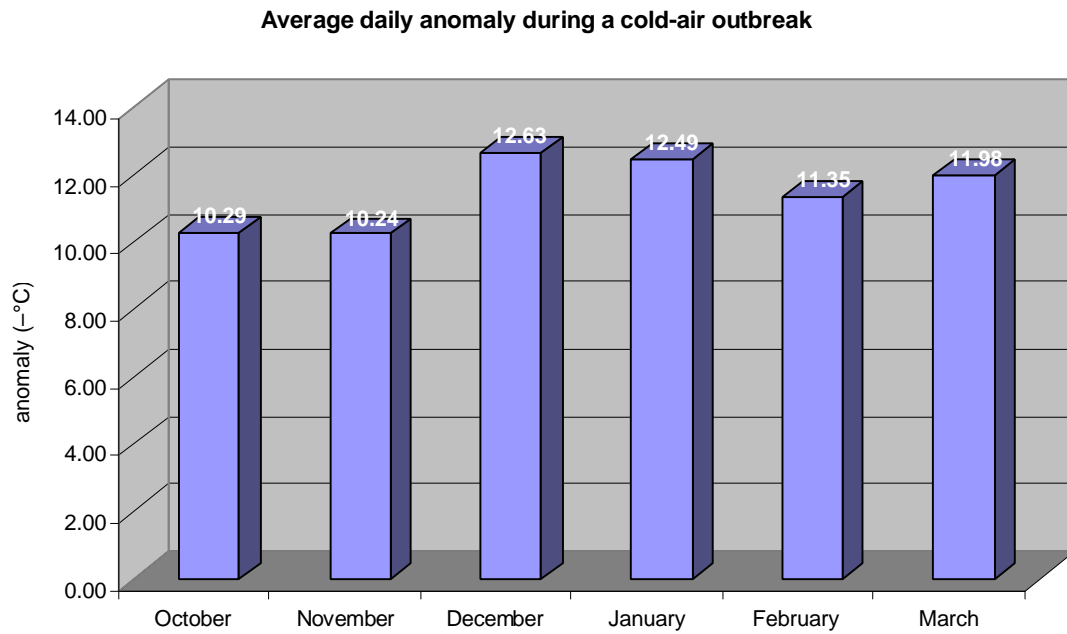
# AVERAGE DAILY ANOMALY WHEN OUTBREAK CONDITIONS EXIST FOR A GIVEN MONTH

	October	November	December	January	February	March
avg. outbreak days	2.4	9.1	8	9	6.7	4.55
avg. degree days	-24.7	-93.2	-101	-112.4	-76.05	-54.5
avg. anomaly	-10.29	-10.24	-12.63	-12.49	-11.35	-11.98

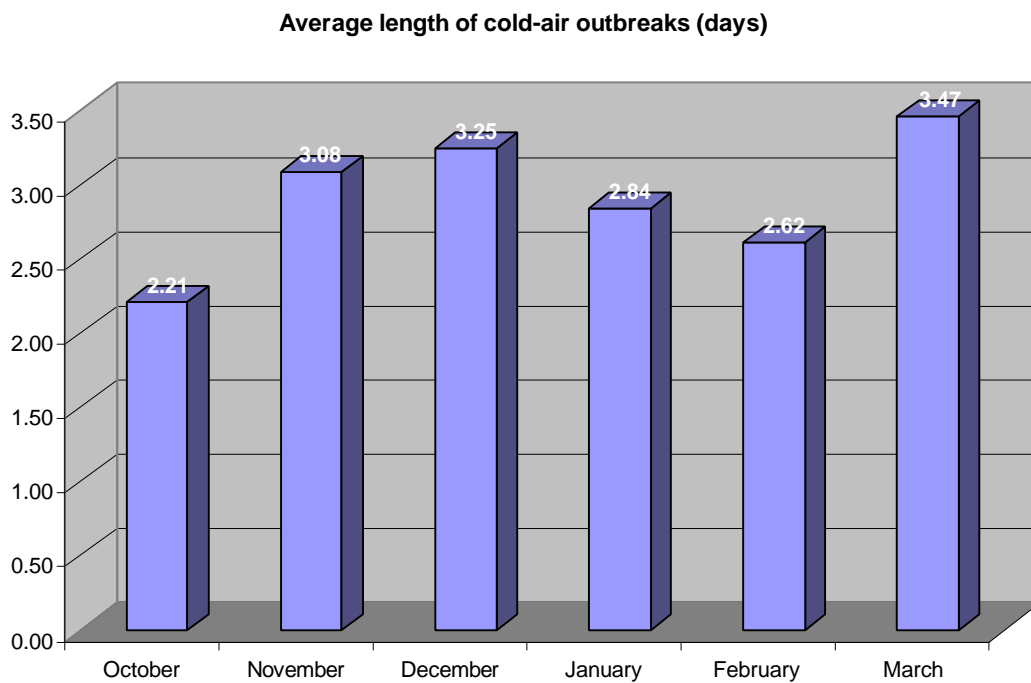
**Figure 7. Variables most useful in predicting optimal times for cloud streets.**



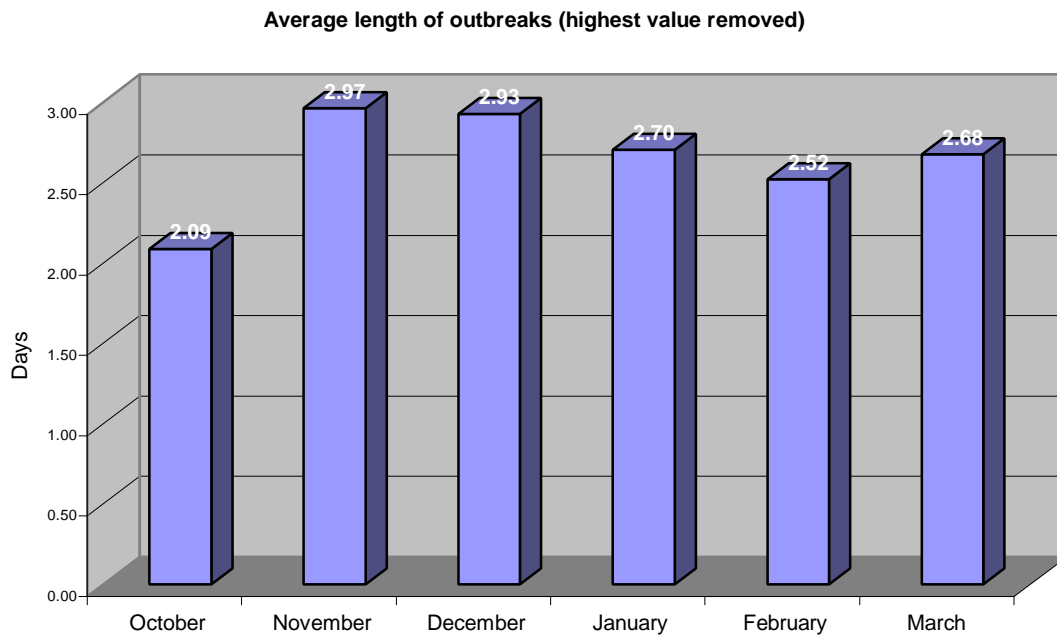
**Figure 8. Climatological odds of outbreak occurrence based on 20-year observation.**



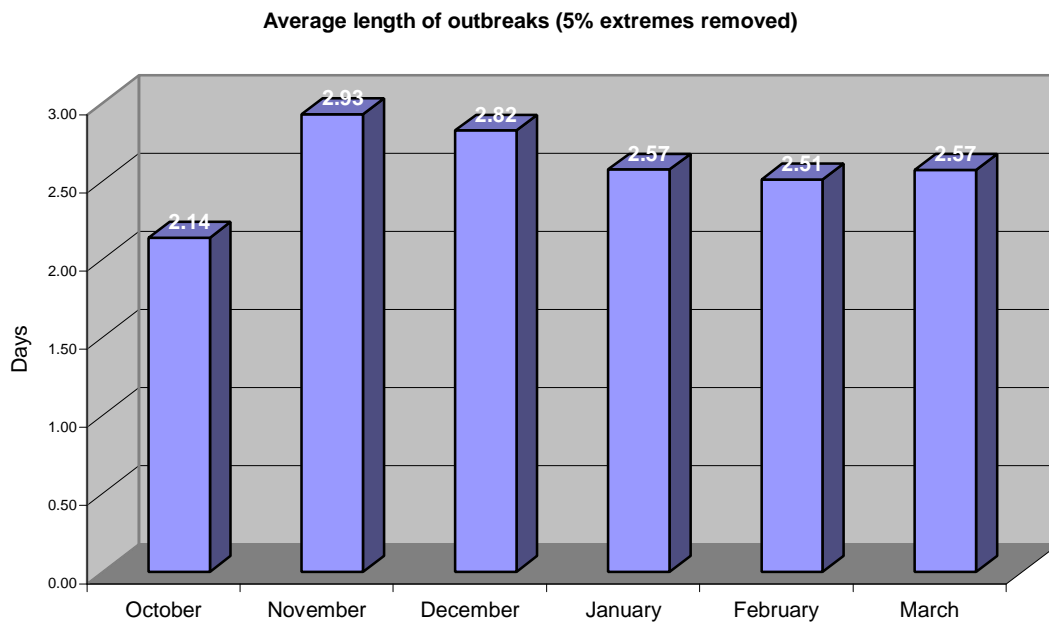
**Figure 9. Climatological average of outbreak severity by month over 20-year period.**



**Figure 10. Average duration of outbreaks by month over 20-year period.**

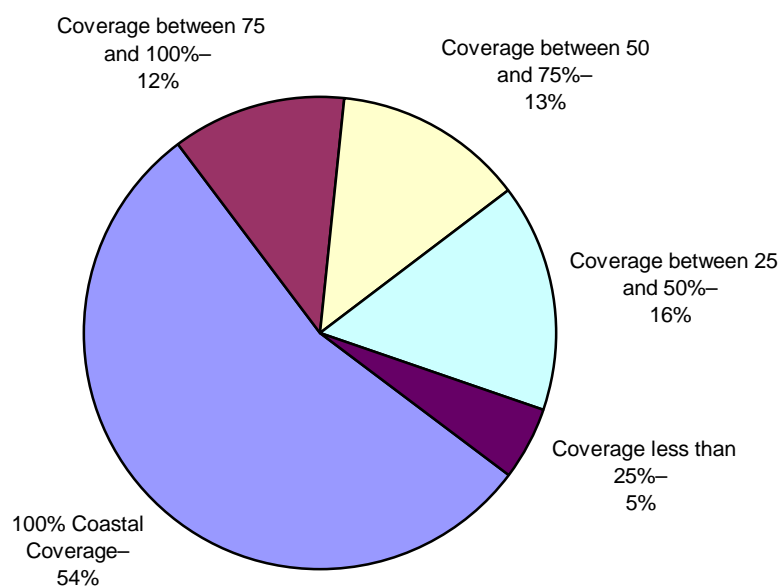


**Figure 11. Average duration of outbreaks by month over 20-year period, with highest monthly value removed.**



**Figure 12. Average duration of outbreaks by month over 20-year period, with the top and bottom 5% extremes value removed.**

### Coastal coverage of cold-air outbreaks, 1980-2000



**Figure 13. Distribution of Atlantic cold-air outbreaks by the percentage of coastline which meets outbreak criteria.**



## Defined regions for geographical analysis

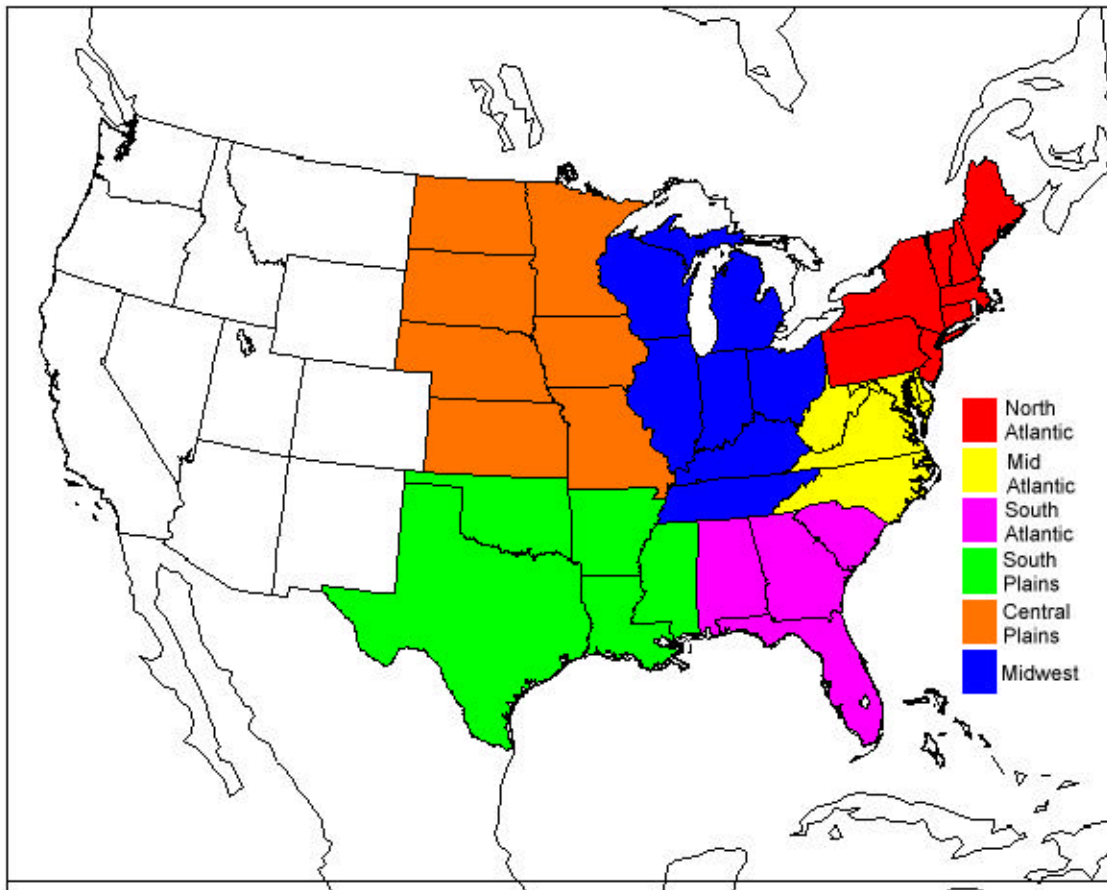


Figure 14. Defined regions used for Figure 15.

	Recorded outbreaks	avg. length of outbreak (days)	avg. max. one day anomaly (°C)	avg. max. total anomaly (°C)	avg. CCV	avg. degree days	avg. daily anomaly
North Atlantic	36	2.14	-14.19	-12.17	0.89	-25.00	-11.69
Mid Atlantic	85	3.45	-11.48	-8.79	0.79	-33.76	-9.80
South Atlantic	105	2.69	-13.30	-10.33	0.74	-29.27	-10.90
South Plains	33	3.18	-19.03	-14.39	0.85	-46.61	-14.65
Central Plains	10	3.50	-19.20	-14.80	0.86	-58.00	-16.57
Midwest	14	3.14	-16.07	-11.93	0.89	-36.36	-11.57

Figure 15. Characteristics of cold-air outbreaks based on the region in which the maximum total anomaly was observed over a twenty-year period.

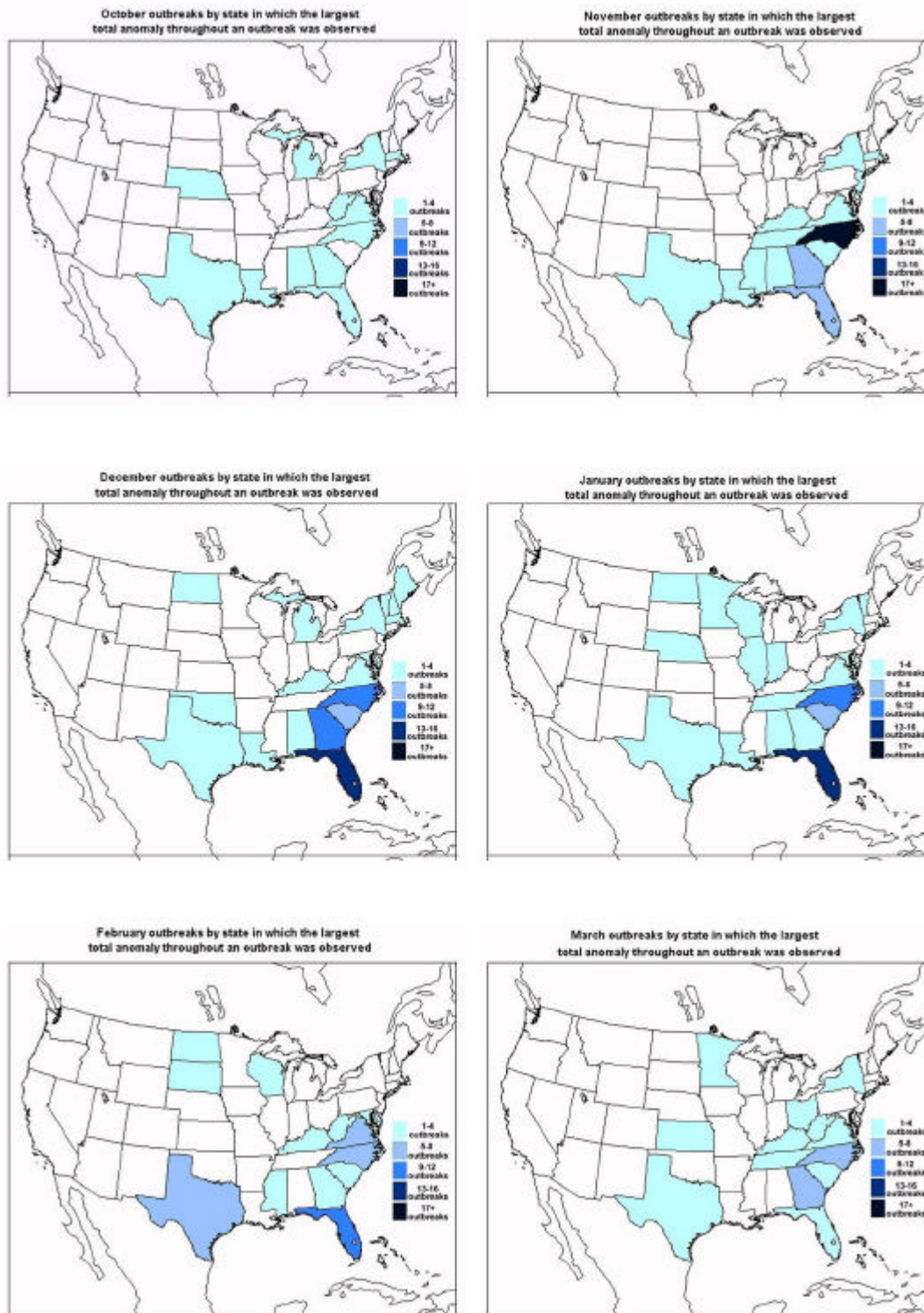


Figure 16. Number of outbreaks in each month with maximum total anomaly observed in a given state over a twenty-year period.

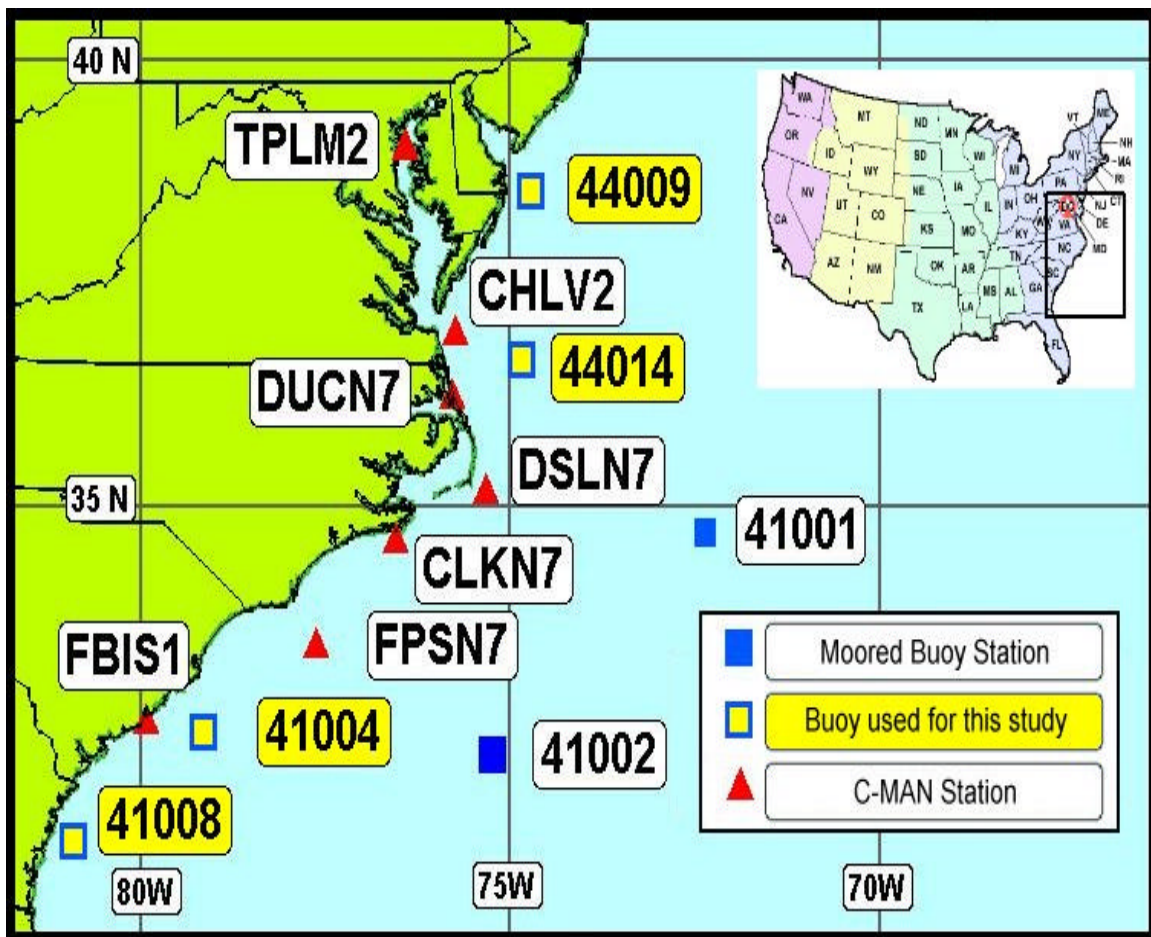


Figure 17. Geographical location of observational buoys whose data was used in this study.

## Difference between sea surface and air temperatures for four buoys off of the southeast Atlantic coast

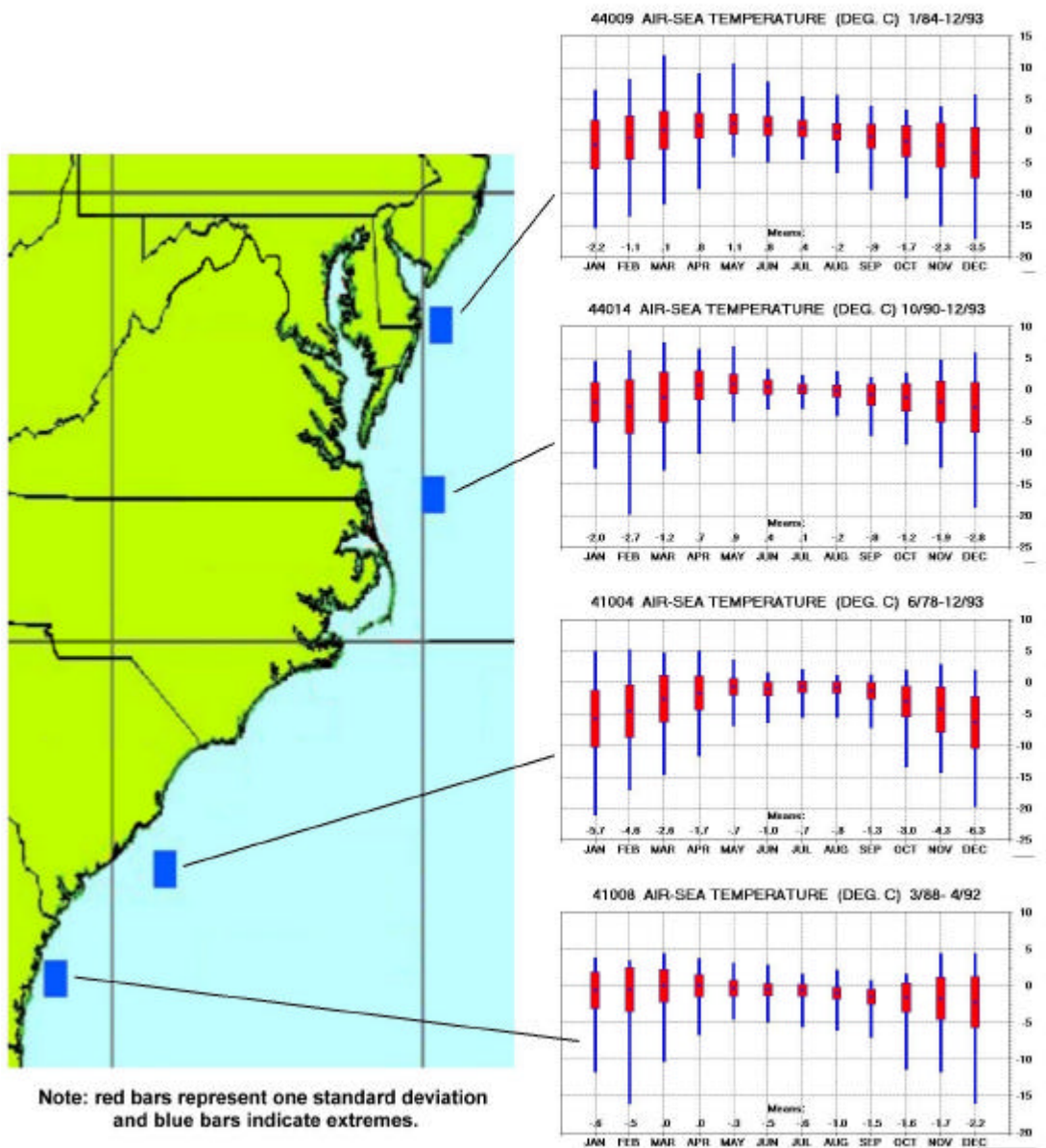


Figure 18. Air-sea temperature differences, as observed by four buoys off the Atlantic coast.



## Peak wind gusts for four buoys off of the southeast Atlantic coast

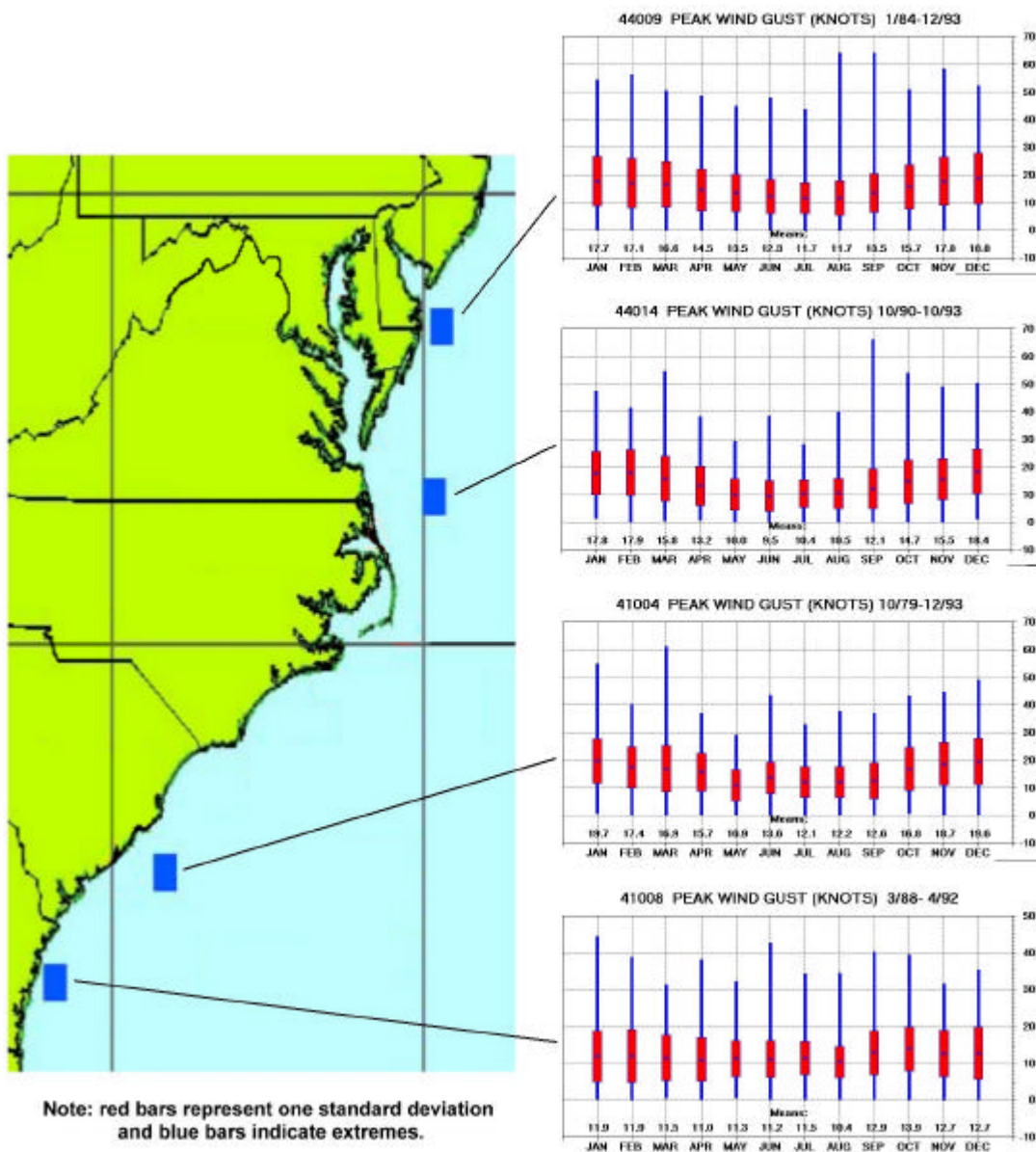


Figure 19. Peak wind gusts, as observed by four buoys off the Atlantic coast.